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A SEARCH FOR DENSE GAS IN QUIESCENT BOK GLOBULES

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ABSTRACT

This study demonstrates crucial differences between quiescent Bok globules and dark cloud cores. Seventeen small, quiescent Bok globules were probed for the molecular lines of NH_3 ($J, K = 1, 1$) and HC_3N ($J = 4 \rightarrow 3$) using the Haystack telescope. The spectra have 3 σ integrated line intensity upper limits generally less than 0.1 K km s^{-1}. The upper limits are less than about 10% of the brightness of TMC-2 in the NH_3 (1, 1) line and less than about 30% of the brightness of TMC-2 in the HC_3N ($4 \rightarrow 3$) line. Both lower chemical abundances of NH_3 and lack of sufficiently dense gas columns through these globules are responsible for the absence of detectable lines. A simple statistical equilibrium analysis suggests that these globules have *mean* volume densities and NH_3 abundance factors of 4–5 lower than seen in dark cloud cores. Our upper limits do not require lower than normal HC_3N abundances.

Subject headings: ISM: clouds — ISM: molecules — radio lines: ISM

1. INTRODUCTION

Isolated, small Bok globules form the simplest subset of molecular clouds which can form stars (Clemens & Barvainis 1988, hereafter CB; Yun & Clemens 1990). Since the presence of dense ($n > 10^4$ cm^{-3}) cores is strongly correlated with sites of recent star formation (e.g., Myers & Benson 1983, hereafter MB), currently starless Bok globules can be probed with dense core-tracing molecules like NH_3 and HC_3N to assess the potential star-forming ability of these globules and to characterize the present physical nature of their cores.

Statistical equilibrium models (non-LTE) of the ($J, K = 1$, 1) inversion transition of NH_3 show that at kinetic temperatures of 10–20 K, detectable line-emitting regions have mean volume densities usually greater than 1×10^4 cm^{-3} (MB). Snell et al. (1981) show that at 10 K, HC_3N ($J = 4 \rightarrow 3$) is excited at somewhat lower densities (a few times 10^3 cm^{-3}), provided that the line is optically thin. However, Sorochenko, Tolmachev, & Winnewisser (1986) find that the HC_3N lines often have nonnegligible optical depth, thus suggesting that the analysis of Snell et al. (1981) gives a lower limit to densities. Bok globules with sufficient mean volume densities (greater than 10^4 cm^{-3}) should show NH_3 (1, 1) and HC_3N ($4 \rightarrow 3$) lines, as long as there is no significant beam dilution, and as long as these species are in normal gas-phase chemical abundances.

The nature of chemical abundances is crucial to understanding molecular line emission in small Bok globules. Although kinetic temperatures of Bok globules have been found to be similar to these in many dark clouds (about 10 K), the small size, relatively low opacity ($A_v \sim$ 1–2 mag), and isolation of globules suggest that molecular chemistry driven by interstellar UV radiation could affect equilibrium abundances of many molecular species.

To address these issues, a sample of small, quiescent globules has been selected from the CB catalog. The quiescence criterion was met by selecting CO ($J = 2 \rightarrow 1$) line strengths less than about 5 K and CO linewidths less than about 2 km s^{-1} and by choosing *IRAS* spectral energy distributions which rise sharply to $\lambda = 100$ μm, indicating very cold dust temperatures (10–20 K), and which contain no *IRAS* point sources. Angular sizes were determined via measurements of cloud images on the POSS O and E plates, with globules for this study selected to be less than about 4′ in diameter. A 17 member subset of the large number of qualifying globules was selected because of the availability of *V*-band CCD photometric and polarimetric images of this subset (Clemens & Leach 1987; Kane et al. 1994).

In § 2, details of the dense gas observations and method of analysis are presented. In § 3, the results are presented, followed in § 4 by a discussion of likely causes for the lack of dense gas detection.

2. OBSERVATIONS AND DATA ANALYSIS

The sample of Bok globules observed is listed in Table 1. Positions were determined by a fast mapping study of the globules in ^{12}CO and ^{13}CO at the Five College Radio Astronomy Observatory during 1992 December, using the QUARRY 15 element focal plane array. Each globule was mapped with one or two QUARRY 5 × 3 (50″ beam) footprints. The orientation angle of the long side of the QUARRY footprint was chosen in each case to align with the position angle of the major axis of the globule, as cataloged in CB. Positions in Table 1 refer to ^{13}CO peaks of integrated intensity found in this mapping study and are sometimes offset from the cataloged positions in CB.

The sample of globules was observed in 1993 June and July with the 36.6 m telescope at Haystack Observatory. The inversion transition of NH_3 ($J, K = 1, 1$) ($\nu = 23.6945$ GHz) was observed with a tunable 21.2 to 25.4 GHz maser receiver. The typical system temperature was around 120 K. The rotational line of HC_3N ($J = 4 \rightarrow 3$)($\nu = 36.3923$ GHz) consists of several hyperfine components, of which the strongest are $F' \rightarrow F = 5 \rightarrow 4$, $F' \rightarrow F = 4 \rightarrow 3$, and $F' \rightarrow F = 3 \rightarrow 2$. These lines were observed simultaneously with a tunable 35.5 to 49

TABLE 1

STARLESS BOK GLOBULE CORES

Cloud Number	Right Ascension (B1950)	Declination (B1950)	V_{lsr} (km s^{-1})[a]
CB 4	00h36m16s	+52°35′30″	−11.3
CB 16	03 59 14	+56 42 40	−2.2
CB 17	04 00 35	+56 48 30	−4.7
CB 24	04 54 33	+52 11 20	4.6
CB 25	04 55 07	+51 59 20	5.2
CB 27	05 01 00	+32 43 20	6.9
CB 67	16 47 35	−19 02 20	4.6
CB 110	18 03 00	−18 26 00	6.1
CB 148	18 30 12	−26 03 50	6.5
CB 161	18 51 13	−07 29 40	12.6
CB 183	19 11 06	+16 29 30	6.6
CB 195	19 32 27	+12 14 10	9.6
CB 202	19 40 20	+18 45 00	18.1
CB 211	19 57 43	+24 26 30	6.9
CB 228	20 49 59	+56 04 30	−1.7
CB 235	21 54 42	+58 45 50	−1.8
CB 246	23 54 12	+58 17 50	−0.5

[a] CO velocities from CB.

GHz maser receiver which operated with a typical system temperature of 200 K. Observations were made in frequency-switching mode with offsets of 0.66 MHz for HC_3N and 0.22 MHz for NH_3. Telescope pointing was accurate to 5″ rms, confirmed via observations of Venus, Jupiter, and H_2O maser sources. All globules were observed using the Haystack system for at least 1 hr total, in each of NH_3 and HC_3N. TMC-2 was monitored as a reference source (Fuller & Myers 1993, hereafter FM).

The data were reduced as follows. Telescope monitoring software converted all spectra into T_A^* units, via use of vane-calibrated system temperatures. Spectra obtained over 10 minute intervals were averagd with equal weighting with other (typically three to six) spectra for that globule in that particular set of observations. Baselines were subtracted, the spectra folded, and then rebaselined. These final spectra were averaged with inverse rms squared weighting with all other final spectra for each globule. From these weighted average spectra, line integral limits were calculated across a 0.6 km s^{-1} window centered at the CO velocity for each cloud (CB).

3. RESULTS

The results are summarized in Table 2. Integrated intensity upper limits (3 σ) are listed in all cases, with line integrals expressed both in units of K km s^{-1} and as a ratio relative to the line integral for TMC-2. Finally, 3 σ upper limits to inferred total NH_3 and HC_3N column densities are listed, following Martin & Barrett (1978) and Lis & Goldsmith (1991), respectively. Figures 1 and 2 compare our spectra of TMC-2 with the spectra of the globule having the highest intensity upper limit and with the spectra of the globule having the lowest rms noise, for NH_3 and HC_3N, respectively.

The observations were designed to detect dense ($n > 10^4$ cm^{-3}) gas. The ranges of column density limits obtained ($2.8 \pm 0.3 \times 10^{13}$ cm^{-2} for NH_3, $9.4 \pm 3.2 \times 10^{11}$ cm^{-2} for HC_3N) were sufficiently low to reveal any dense gas present.

TABLE 2

INTEGRATED LINE INTENSITY LIMITS

CLOUD NUMBER	NH_3 $\int T_A^* dv$ (mK km s^{-1})[a]	NH_3 $\int T_A^* dv$ (mTMC)[b]	N_{NH_3} (cm^{-2})[c]	HC_3N $\int T_A^* dv$ (mK km s^{-1})[a]	HC_3N $\int T_A^* dv$ (mTMC)[b]	N_{HC_3N} (cm^{-2})[d]
CB 4	21	23	2.4×10^{13}	64	174	7.0×10^{11}
CB 16	26	29	2.5×10^{13}	98	264	1.1×10^{12}
CB 17	24	27	2.4×10^{13}	39	106	4.3×10^{11}
CB 24	37	41	2.7×10^{13}	92	250	1.0×10^{12}
CB 25	47	52	2.8×10^{13}	60	161	6.6×10^{11}
CB 27	19	21	2.3×10^{13}	76	205	8.4×10^{11}
CB 67	34	37	2.6×10^{13}	96	258	1.1×10^{12}
CB 110	32	35	2.6×10^{13}	126	341	1.4×10^{12}
CB 148	81	90	3.3×10^{13}	138	374	1.5×10^{12}
CB 161	62	69	3.0×10^{13}	63	171	6.9×10^{11}
CB 183	59	65	2.9×10^{13}	105	284	1.2×10^{12}
CB 195	63	70	3.0×10^{13}	100	270	1.1×10^{12}
CB 202	57	64	2.9×10^{13}	103	278	1.1×10^{12}
CB 211	62	69	3.0×10^{13}	114	307	1.3×10^{12}
CB 228	54	60	2.9×10^{13}	57	153	6.3×10^{11}
CB 235	38	42	2.7×10^{13}	60	163	6.6×10^{11}
CB 246	63	70	3.0×10^{13}	51	138	5.6×10^{11}
Mean	44	51	2.8×10^{13}	85	229	9.4×10^{11}
Dispersion	18	20	0.3×10^{13}	28	77	3.2×10^{11}

[a] 3 σ upper limits of line intensities across a 0.6 km s^{-1} wide window centered at the CO velocity (CB).

[b] 1 mTMC = 10^{-3} $\int T_A^* dv$ for TMC-2. For NH_3, the TMC line integral is 0.9 K km s^{-1}. For HC_3N, the integral is 0.37 K km s^{-1}.

[c] 3 σ upper limits of total column densities, based on the method of Martin & Barrett 1978, assuming a main-beam efficiency of 33% and total optical depths around 0.1.

[d] 3 σ upper limits of total column densities, based on method of Lis & Goldsmith 1991, assuming a main-beam efficiency of 25% and optically thin lines.

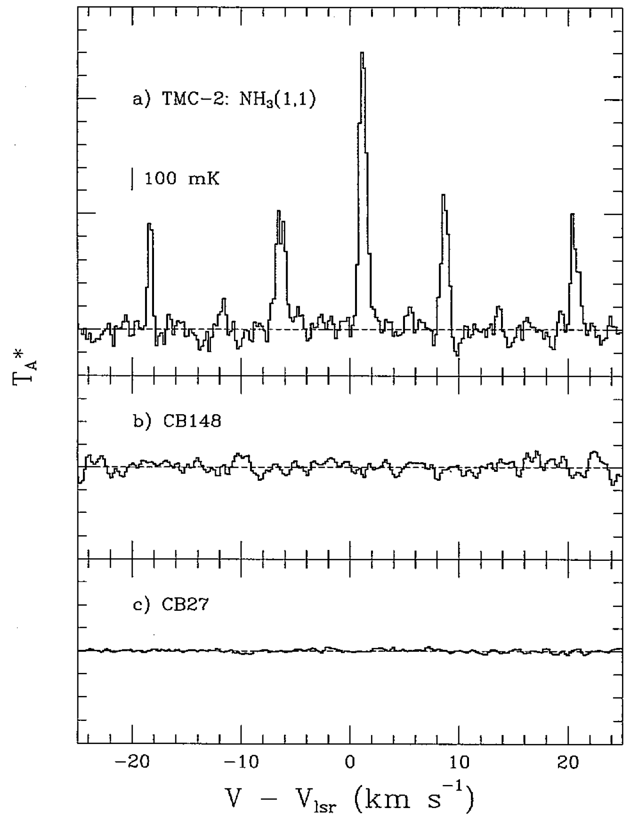

FIG. 1.—Observed NH_3 spectra of (*a*) the reference source TMC-2 (Fuller & Myers 1993); the source with largest upper limit to line intensity, CB 148; and the source with the smallest rms noise, CB 27. Velocities are calculated relative to the CO line-center velocity from CB. Temperatures are in T_A^* units, and the 100 mK key applies to each spectrum.

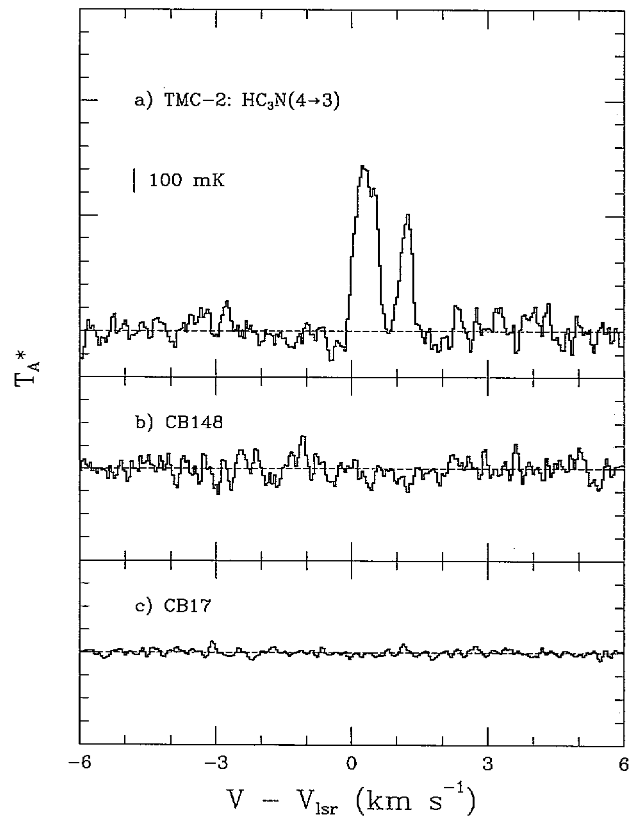

FIG. 2.—Observed HC_3N spectra of (*a*) the reference source TMC-2; the source with the largest upper limit to line intensity, CB 148; and the source with the lowest rms noise, CB 17. Velocities are calculated relative to the CO line-center velocity from CB. Temperatures are in T_A^* units, and the 100 mK key applies to each spectrum.

We detect no evidence of significant reservoirs of dense gas in this sample of small Bok globules.

4. DISCUSSION

There are several possible explanations for the dearth of lines in our observations. First, the globules may have cores which do not have sufficient quantities of dense gas to excite detectable line emission in NH_3 or HC_3N. Second, these species may be underabundant due to gas-phase or grain chemistry effects in the presence of an elevated UV radiation field, relative to the more shielded conditions in dark clouds.

The presence of a hidden central condensation with density and temperature properties similar to those in TMC-2 would require the condensation to cover less than about 30% of the NH_3 beamwidth of 90″ (i.e., 25″), or 0.02 pc diameter. With densities near 10^4 cm^{-3}, the total mass of such condensation would be no more than about 0.1–0.2 $M_\odot$. Given that virial and ^{13}CO column density mass estimates suggest that there are generally about 10 $M_\odot$ of gas in each globule (CB), such very low mass condensations would be quite different in nature than the more massive concentrations (1 to a few $M_\odot$) in dark cores. FM have observed that most NH_3 and HC_3N sources have FWHM map sizes ranging from 0.05 pc to 0.12 pc, about twice as large as the largest possible globule condensations and therefore at least 10 times as massive.

A quantitative assessment of the relative importance of abundances and central densities is achieved via a simple statistical equilibrium analysis. Observationally, there are two constraints. First, the *mean* visual extinction through the globules is 1–2 mag, implying total H_2 column densities of 1 to 2×10^{21} cm^{-2}. Dark cloud cores, in contrast, have mean visual extinctions in the range of 5–6 mag (Benson & Myers 1989; hereafter BM). *Peak* visual extinctions through globules range from 2–5 mag, while those for dark cloud cores may be many tens of magnitudes. Second, the mean and dispersion of the rms noise in the sample of NH_3 spectra are 25 ± 10 mK, and those of the HC_3N sample are 47 ± 16 mK. Like dark cloud cores (BM; FM), these globules have line widths ~0.6 km s^{-1}, the mean ^{13}CO value. The characteristic kinetic temperature of this globule sample is 10 K (CB), similar to dark cloud cores.

Additionally, the fraction of the total column density (with $n > n_{crit}$) sampled with the NH_3 and HC_3N line probes must be estimated. Globules were modeled to have volume density plateaus extending to about 10% of their total radii and to have $n(r) \propto r^{-1.5}$ profiles outside their plateau radii (Yun & Clemens 1991). For 0.12 pc globules with 2×10^{21} cm^{-2} total column density, the fraction of the total H_2 column with $n \geq 1 \times 10^4$ cm^{-3} is 0.5 (appropriate for NH_3), and with $n \geq 5 \times 10^3$ cm^{-3} is 0.7 (appropriate for HC_3N).

From this modified column density constraint, mean volume densities were calculated for plausible values of globule size. By balancing the spontaneous emission rate against the collision and stimulated emission rates at each density, excitation temperatures were derived from the observational noise temperature constraints and the assumed 10 K kinetic temperature. Line opacities were calculated from the excitation temperatures (and in all plausible cases were optically thin), and from these opacities, abundances were derived. Using H_2 column densities inferred by observed mean visual extinctions, molecular column densities were then calculated. Finally, these model molecular column densities were compared to the upper limits on column densities predicted by the observed upper limits on line-integrated intensities.

If the globules in this sample are assumed to have the same size as dark cloud cores (0.12 pc; see BM and FM), the globules' mean volume density is 18% of the dark cloud core mean, or about 5×10^3 cm^{-3}. At this density and 10 K temperature, the statistical equilibrium abundances have mean values and dispersions (from the individual globule 3 σ integrated intensity limits) *relative to dark cloud cores* of 0.26 ± 0.12 for NH_3, quite underabundant, and 1.06 ± 0.65 for HC_3N, essentially normally abundant. For dark cloud cores $X_{NH_3} = 2.8 \times 10^{-8}$ (BM), and $X_{HC_3N} = 3.2 \times 10^{-10}$ (FM and references therein). Thus, the ranges of 3 σ upper limits to globule column densities are $2.5 \pm 1.2 \times 10^{13}$ cm^{-2} and $1.2 \pm 0.7 \times 10^{12}$ cm^{-2}, for NH_3 and HC_3N, respectively, in good agreement with the values in Table 2.

Ammonia is principally formed through a series of reactions of ionized amine radicals with molecular hydrogen (Federman, Huntress, & Prasad 1990). Ammonia is principally destroyed either via UV dissociation by photons more energetic than 10.2 eV or by reaction with C^+ or other more complex ions. However, the overall destruction rate of NH_3 via UV photons is modeled to be *five orders of magnitude slower* than its production rate (from coefficients quoted in Duley & Williams 1984, pp. 213, 240, 244), for kinetic temperatures of 10 K and visual extinction around 1 mag, conditions similar to those present in the cores of these globules. A similar scenario can be built for cyanoacetylene, whose chemistry is described by Mitchell, Huntress, & Prasad (1979). The principle formation and destruction routes for HC_3N, those with He^+ and carbon-bearing ions, do not involve UV radiation. Therefore, for both species, enhanced UV dissociation as the cause of decreased equilibrium abundances is at best a secondary explanation for the lack of detected lines.

Turner (1994, hereafter T94) completed an extensive ^{13}CO and $C^{18}O$ survey of CB clouds which partially overlaps the sample studied in this paper. Among those T94 CB clouds which were observed here, no hydrostatic model nor empirical power law produced central densities greater than 2.8×10^3 cm^{-3}, factors of 4 and 2 lower, respectively, than those required in order to excited detectable NH_3 (1, 1) and HC_3N ($4 \rightarrow 3$) emission. The models in T94 suggest that UV dissociation, although still a possible means of altering equilibrium abundances of molecules like NH_3 and HC_3N, probably is secondary in importance to the role that subcritical core densities play in inhibiting emission in the transitions observed. A multitransition study of NH_3 and/or HC_3N with greater sensitivity could be useful in further distinguishing density and abundance effects. The results from this *Letter* are consistent, but by no means uniquely prove, that the *central* density in Bok globules is lower than in dark cloud cores. However, models described in this *Letter* support the observations to show that *mean* volume densities and column densities are likely to be a factor of 5 lower in Bok globules than in dark cloud cores.

5. CONCLUSIONS

A sample of 17 small, quiescent Bok globules from the CB catalog was examined in the (1, 1) inversion line of NH_3 and in the ($J = 4 \rightarrow 3$) rotational line of HC_3N. The following conclusions have been reached:

1. The 3 σ upper limits of line integrals are consistent with statistical equilibrium models indicating mean densities less than about 5×10^3 cm^{-3}, insufficient to produce detectable line emission in these transitions. It appears that these globules have mean densities which are much lower than those of dark, star-forming cloud cores but which are more like those seen in high-latitude cirrus clouds. This may indicate that these globules have not had sufficient time to undergo core contraction.
2. Simple statistical equilibrium calculations employing $r^{-1.5}$ density laws and our observational limits require the globules to have NH_3 abundances reduced by at least a factor of 4 compared to dark cloud cores, while HC_3N abundances are not required to be abnormal.

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